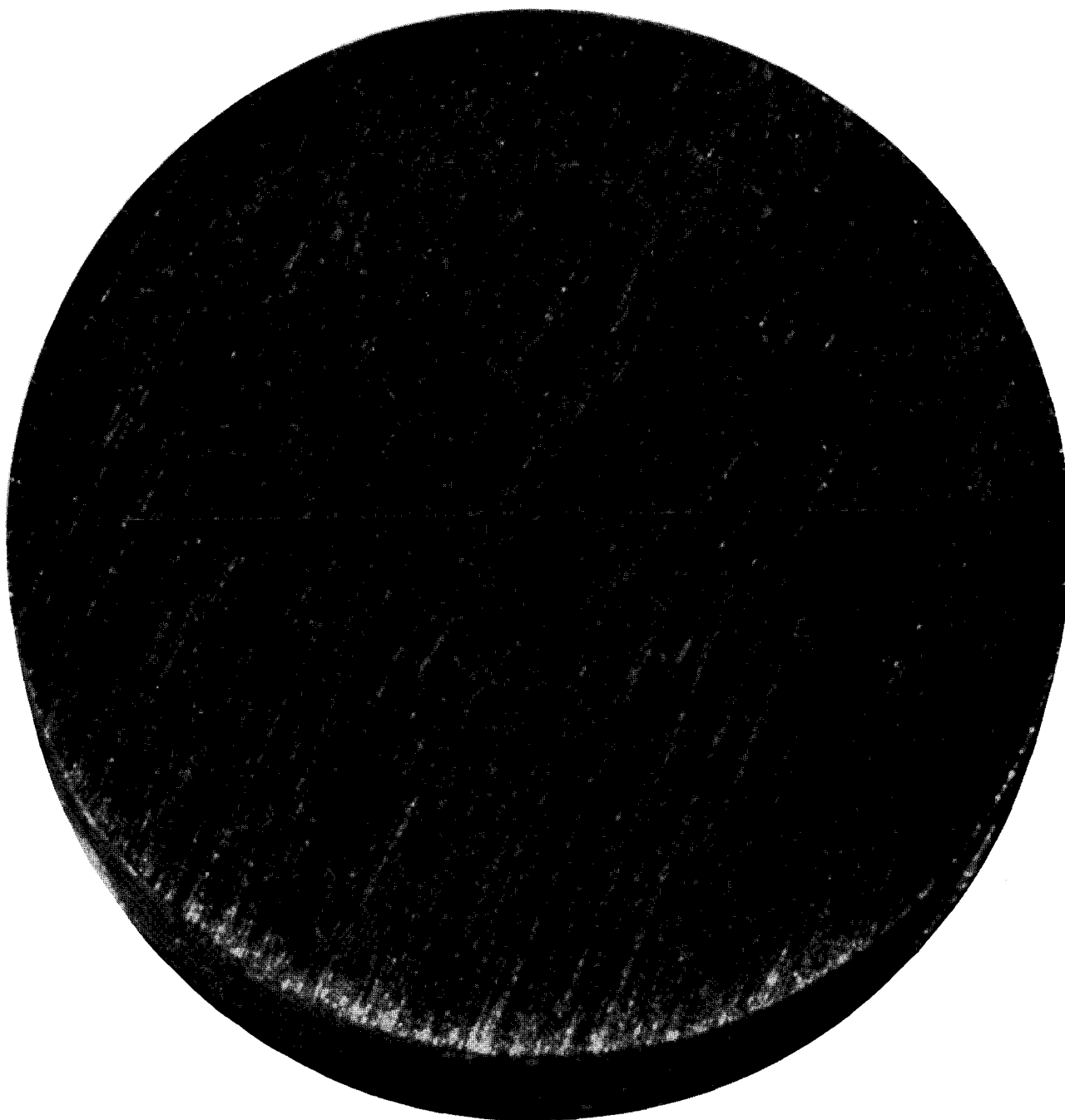


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High-Resolution Magnetic Recording Structures

Abstract: Design concepts are established for several high-resolution magnetic recording structures, and their application demonstrated. The conventional ring head is treated and two new devices are described. A probe-type unit is discussed which shows promise in high-density vertical magnetic recording. A wire-grid array is also advanced to outline a unique conceptual approach to the achievement of higher resolution.

1. Introduction

Based upon a theory developed for magnetic data recording, it has been shown that it is possible to evaluate recording structures (head-surface configurations) with respect to recording resolution by examining the degree of magnetic coupling between the recording-head coil and the magnetic storage layer along the direction of surface motion.¹ In this previous paper a unique head design was established within the framework of a given set of restraints. The particular magnetic head is the one used for the disk file of the IBM 305 RAMAC.

The present paper generalizes the design theory considering various magnetic structures derived specifically to maximize recording resolution. The structures studied provide both the writing and reading functions involved in data storage. The devices considered are thus characterized by the fact that they provide an output signal proportional to the rate of flux change through a winding.

Various techniques of analysis are presented, the choice being based upon the type of structure involved. The experimental agreement with analysis is excellent from an engineering design point of view where experimental results are available. These cases serve to justify the validity of the general application of the design concepts and the resulting evaluations. One structure, a probe device, is presented for possible use in high-density recording and is felt to represent a significant new contribution to the art of magnetic head design. This paper deals primarily with recording resolution and only brief mention of the practical value of the devices is made. The latter aspect depends upon the state of the art in other technologies and it was felt this should not detract

from a general study of the subject of magnetic focusing for magnetic data storage. Time-dependent focusing concepts are not considered.

2. Review of concepts

Magnetic data recording involves the storage and sensing of binary information, utilizing two states which are capable of being differentiated. The recorded regions (bit intervals) corresponding to the values of a binary variable (0 and 1) may themselves be formed from alternating combinations of the two basic saturated conditions of surface magnetization used. Since the two states of saturation on the recording surface are established by control of the sense of flux set up in the recording structure, and the particular direction of this flux is only a matter of sign, it is necessary only to consider one fundamental input signal. For example, in the NRZ (non-return-to-zero) scheme of recording the surface is continually saturated during writing, in one direction for a 0 and in the opposite sense for a 1. Any input is then composed of a succession of alternating step-like changes in writing current. The basic input wave form is therefore a step function. Biased discrete-pulse recording, in which the surface is continuously saturated in the negative sense during writing except upon the occurrence of a 1 for which a positive saturating pulse is applied during the bit interval, would have as the basic input wave form an impulse-like function.

It has been shown¹ that the over-all input-output transfer process can be treated by consideration of the characteristic output response arising from the single basic input

wave form. This fact is based upon the validity of the application of the principle of superposition. The reasons for this will be outlined briefly.

On read back, the existing magnetic field is due to the recorded-surface magnetization and is thus extremely weak. The magnetic head then will behave very nearly as a linear element. The output signal results from a change in magnetization. A step change in magnetization represents the limiting ideal.

Reading resolution is defined as the distance along the recorded track over which such a step change in magnetization produces an effective differential change in flux. Only distance concepts are meaningful when considering recording resolution, the relation between distance and time being fixed by the surface velocity.

It is shown¹ that the principle of reciprocity can be applied to the reading process. Hence, the magnetic-field distribution at the storage surface, resulting from energizing the reading coil with a small current just sufficient to produce the same field level as exists on read-back, can be related directly to the reading resolution. This is possible since this field gives a measure, at each surface point, of the degree of coupling between the coil and a point magnetic source at that position.

In considering the process of writing, writing definition is defined as the distance in the direction of surface motion over which the change in the sense of surface saturation occurs. The magnetic-writing field which is of interest is the one set up along the magnetic surface when the writing coil is energized with a current of sufficient magnitude to produce surface saturation. It is common practice in recording structures to use the same coil for both writing and reading. Further, even though the field intensities involved in reading and writing differ by orders of magnitude, the nominal field distribution applying to reading resolution is similar to that obtained when writing. Writing definition, however, is concerned only with the condition of magnetization left on the surface after the surface region has left the vicinity of the magnetic head. For a step-input change in saturation writing current, only the surface region under the trailing half of the recording structure at the instant of switching need be considered. Once the writing field is switched, all the track that will later pass the magnetic head will be traversing an identical magnetizing field, and so will be uniformly magnetized. When the central plane of the head orients the surface passing this point to a uniformly saturated condition, all cross sections of the track that pass this point are similarly aligned. A similar situation exists for a recorded impulse. Since the surface exhibits a saturation characteristic, the width of the transition zone between the two directions of saturation will be very much less than the extent of the writing field. This "threshold" aspect is in contrast to the situation prevailing on read back. Reading resolution is hence far worse than writing definition.

Since the principle of superposition will be valid as long as a change in writing current does not affect the previously recorded transition zone, only a single basic input wave form need be considered in the study of the

influence of recording resolution upon the output signal. More important, in the evaluation of a magnetic structure for recording resolution, only reading resolution need be considered except where, due to the magnetic properties of a particular storage surface, the ratio between reading resolution and writing definition deteriorates to appreciably less than four or five to one. Note that the reading resolution and the writing definition are defined in terms of distance and the higher or better the reading resolution, for example, the shorter or smaller this distance. It may likewise be noted that any improvement in reading resolution will normally result in an improvement in writing definition since basically the same magnetic-field configuration is involved.

Henceforth the term "recording resolution" will imply reading resolution since these two terms are essentially equivalent. Recording resolution is a function of the magnetic head-storage surface configuration, as the performance of the system can be discussed only in terms of their magnetic coupling. All devices are essentially two-dimensional since the head design proper in conjunction with the surface establishes recording resolution while other tolerances and factors influence track density. Track width is in practice, then, effectively infinite compared with the parameters influencing recording resolution.

Considering the common ring-type structure shown in Fig. 1, the following relation may be written,

$$e(\bar{x}) \propto [vNd\phi_h(\bar{x})/d\bar{x}], \quad (1)$$

where e is open-circuit output voltage and ϕ_h is reading coil flux. The variable $\bar{x}$ represents the relative disposition in the x direction of the recorded magnetization with respect to the magnetic head, i.e., $\bar{x} = vt$. By means of the concept of reciprocity it has been indicated that resolution is fundamentally involved with the x extent of the magnetic coupling between the magnetic-head coil and the recording surface. That is, from Reference 1:

$$de_x(\bar{x}, y) \propto H_x(x, y) dy \quad (2)$$

$$\text{and } de_y(\bar{x}, y) \propto H_y(x, y) dy \quad (3)$$

$$\text{where } de = de_x + de_y. \quad (4)$$

H_x and H_y are the vector components of the magnetic field set up along the differential strip, dy , when the head is energized by a small current as previously described. de_x is the voltage contribution arising from a step change in horizontal magnetization in the plane y and de_y is the voltage contribution due to similar step change in vertical magnetization in the plane y . The constant of proportionality is the same in both these cases. de represents the total incremental voltage obtained from the plane y . The transformation from $\bar{x}$ to x is made since the resolution is not concerned with the location of the recorded information at any particular instant.

The total read-back signal is given by the expression

$$e(x) = \int_{-d/2}^{d/2} de_x(x, y) + \int_{-d/2}^{d/2} de_y(x, y) \quad (5)$$

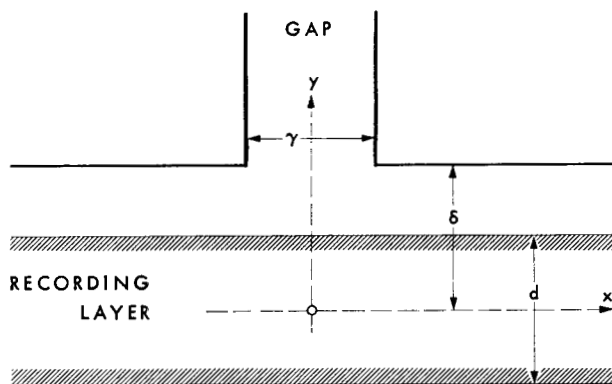


Figure 1 Idealized ring head.

where the integration is with respect to the variable y , d is the recording-layer depth and $e(x)$ represents the recording resolution since it gives the distance in the x direction over which the recording structure is effectively coupled to the storage layer. However, as the only resolution of interest is that corrected for the actual magnetization occurring, a more appropriate expression would be:

$$e(x) = CM_x \left[\int_{-d/2}^{d/2} H_x(x, y) dy + f \int_{-d/2}^{d/2} H_y(x, y) dy \right] \quad (6)$$

where C is a constant and f is the ratio of the vertical component of magnetization to the horizontal component in the uniformly saturated surface. The ratio f is quite important even though the actual transition between directions of saturation is assumed to be a step function. It is considered further that saturation recording implies the storage surface is saturated throughout its depth. When d is very small compared to the other parameters the expression for $e(x)$ reduces to

$$e(x) = CM_x d [H_x(x) + f H_y(x)] \quad (6.5)$$

since H_x and H_y can be assumed constant over the surface cross section.

Another useful relation is the following:

$$\int_{-\infty}^{+\infty} e(x) dx = Nv [\phi_h(\infty) - \phi_h(-\infty)] = 2Nv \phi_h(\infty) \quad (7)$$

where N is the number of reading turns and v is surface velocity. This expression gives a relation between the resolution response-distance pulse area and the flux through the recording-head coil when the entire track is uniformly magnetized. The actual limits of integration need only extend over the range for which $e(x)$ is significant. The relation serves as a check on the correctness of the determination of $e(x)$ since in many cases $\phi_h(\infty)$ can be reasonably estimated.

It is evident that the recording resolution is being established as a function of x rather than a specific number. This procedure allows direct insight into the physical basis for the variation of resolution between structures

and, further, before any cases are particularized, both terms of $e(x)$ will be determined with f left unspecified. The results then can be adjusted to fit cases where f may differ. To obtain comparisons, however, numerical values will be obtained for recording resolution on the basis of the distance between the points where the coupling is reduced to five per cent of the maximum degree of magnetic coupling.

The structures to be considered using this theory are the ring, probe, and wire grid. The methods used include both analytical calculations and resistor-network-analog measurements. Experimental confirmation is included when available.

The relative permeability of the storage layer is quite low, particularly since it is in a saturated condition. Contrasted with the relatively high permeability of magnetic-head materials it may satisfactorily be considered to be the same as air in its effect upon the field distribution of the recording structure. The permeability ratio between the magnetic-head material and air is generally in orders of magnitude. Thus the magnetic-head material properly may be assumed to possess infinite permeability for the majority of objectives here.

3. Ring-type recording heads

First consider an idealized ring-type recording head. As used here an idealized ring head is one whose pole faces extend along the plane of the recording surface a distance many times that of the largest of the parameters indicated in Fig. 1. For this class of ring heads the pole faces for all practical purposes may be considered to extend to infinity on both sides of the gap.

In contact recording $\delta - d/2 = 0$. Except for this restriction the analysis applies equally well to contact as well as non-contact recording. Since the surface is approximately equivalent to air, the calculations need be only in terms of γ and δ . The surface thickness can then be incorporated by summing up the resolution functions for a set of differential strips whose spacing ranges from $\delta - d/2$ to $\delta + d/2$. Since resolution deteriorates with increased spacing, the tendency with increasing d is to increase the signal by the addition of more strips but at the same time to decrease the net resolution, since the addition of strips at progressively greater spacing adds contributions with broader coupling zones.

• a. Case $\delta \gg \gamma/2$

For cases covered by the approximation $\delta \gg \gamma/2$ the following mathematical analysis is applicable (see Fig. 2).

$$H = k/r$$

where k is a constant and $r \approx [\delta^2 + x^2]^{1/2}$.

$$H(o) = k/\delta \quad \text{or} \quad k = H(o)\delta \quad (8)$$

and

$$H_x = H\delta/r = H(o)(\delta/r)^2 \quad (9)$$

where $H(o) = H_{x\max}$.

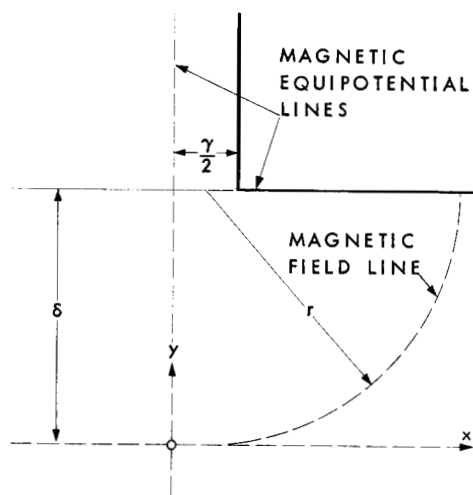


Figure 2 Equipotential boundaries for an idealized ring head.

Further

$$H_y = H(x/r) = H(o)(\delta)(x/r^2). \quad (10)$$

Computation of H_{ym} :

$$\partial H_y / \partial x = H(o)(\delta) \partial / \partial x [x(\delta^2 + x^2)^{-1}] = 0$$

giving $x = \pm \delta$.

Thus

$$|H_{ym}| = H(o)/2. \quad (11)$$

Consider first the resolution in terms of the attenuation of the field intensity, H , without reference to its angle

$$H(o)/H = r/\delta = [\delta^2 + x^2]^{1/2}/\delta.$$

Let $u = x/\delta$

then

$$H(o)/H = (1 + u^2)^{1/2}. \quad (12)$$

By the criterion specified for the computation of the coupling distance, λ , in terms of the attenuation of the degree of coupling to five per cent of its maximum value

$$H(o)/H = 20$$

or $u \approx 20$

$$\text{i.e., } x = 20\delta \text{ or } \lambda = 40\delta. \quad (13)$$

Equation (13) states that under the condition above the resolution is 40 times the head-to-surface spacing. Suppose, however, the surface magnetization is entirely longitudinal, i.e., $f = 0$.

Then

$$H(o)/H_x = (r/\delta)^2 = u^2 + 1 \quad (14)$$

$$\text{or for } H(o)/H_x = 20 \quad (15)$$

$$u \approx 4.5 \text{ or } \lambda_x = 9\delta. \quad (16)$$

(Note at $u = 1$, $H_x = \frac{1}{2}H_{xm}$.)

In this case the recording resolution would be only nine times the spacing. For purely vertical magnetization the field component of interest is H_y and

$$H_{ym}/H_y = H(o)/2H_y = \frac{1}{2}[1/u + u].$$

Setting $\frac{1}{2}[1/u + u] = 20$, $u \approx 40$ or $\lambda_y \approx 80\delta$.

Since $\delta \gg \gamma/2$, λ_x and λ_y are not functions of γ .

The deleterious influence of a vertical magnetization component upon recording resolution with a ring-type structure is readily apparent. It is thus of interest to determine $f = f_{max}$ where f_{max} is defined to be the largest value of f permissible and still have $\lambda_{min} \approx \lambda_x$.

For this $f(H_y) \leq 0.05H(o)$ at $x = 4.5\delta$.

Now for $x = 4.5\delta$,

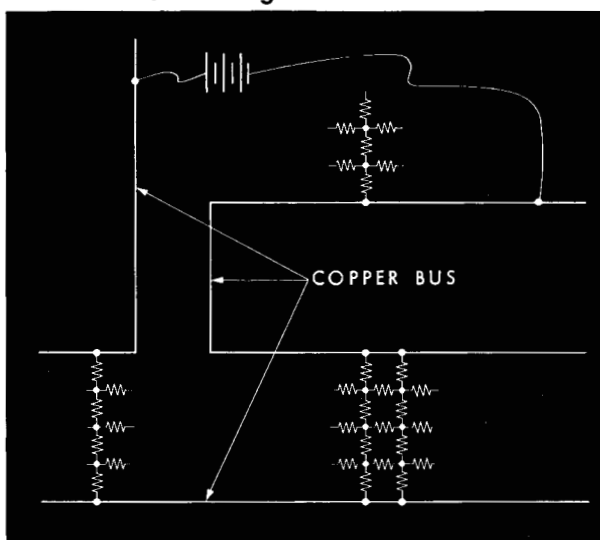
$$H_y \approx H(o)/u.$$

$$\text{Then } f \leq 0.05(4.5) = 0.225. \quad (17)$$

Relation (17) states that if the vertical component of surface magnetization is less than approximately 20% of the horizontal component of magnetization the recording resolution does not suffer. The best resolution attained with an idealized ring head under these conditions is 9 δ . For contact recording a value for δ of between $d/2$ and d should be used. In the contact case $d/2$ represents the mean spacing of the surface differential strips but the influence of the strips separated further than $d/2$ may make the estimate from this value somewhat optimistic. Consider a contact ring head with a gap considerably narrower than the thickness of the recording layer, i.e., a 0.1-mil gap head recording on a 0.6-mil oxide layer. Then

$$\lambda_x = 9(0.3) = 2.7 \text{ mils.}$$

Figure 3 Interconnection method for a resistor-network analog.



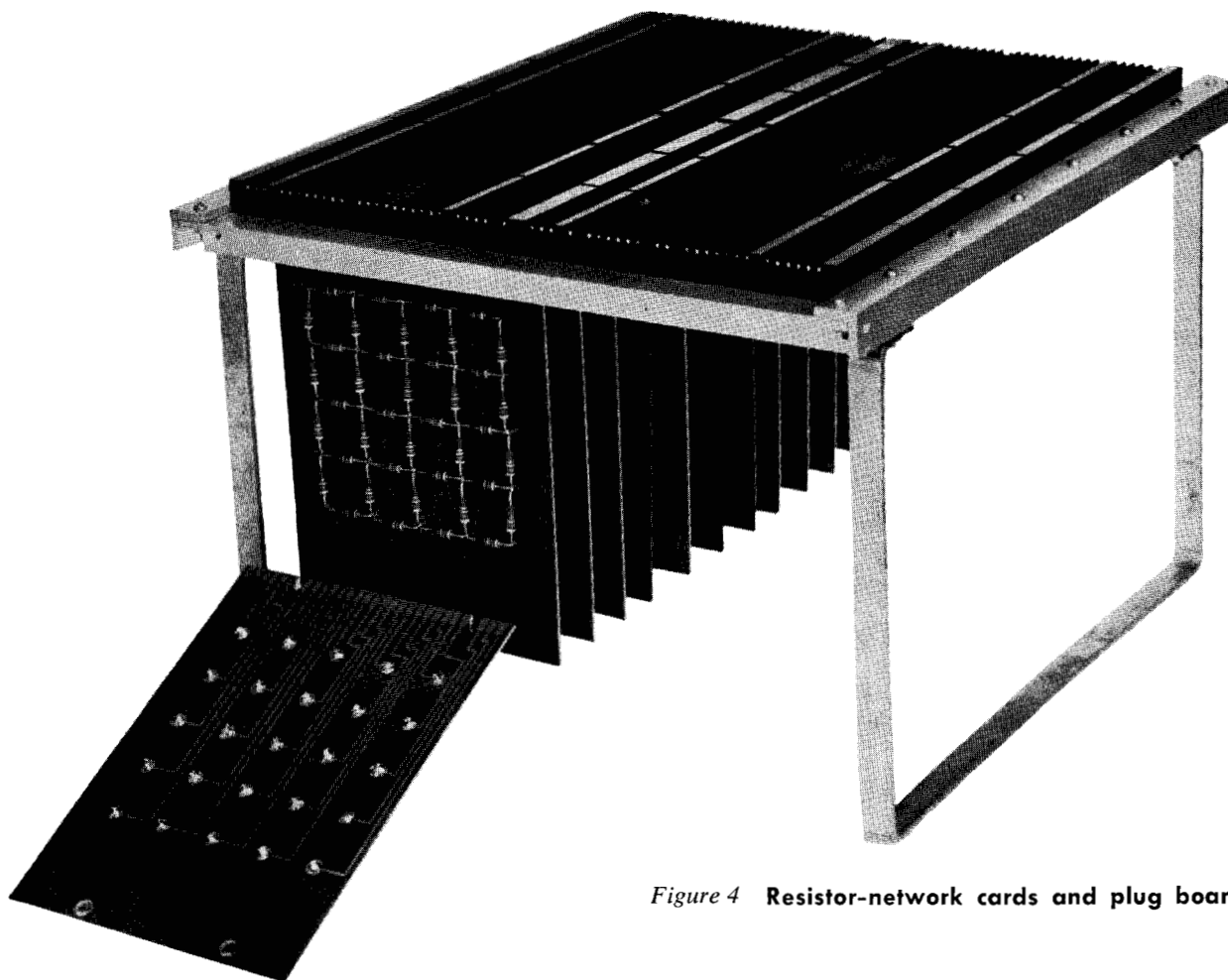


Figure 4 Resistor-network cards and plug board.

This figure agrees well with experimental data for this situation.

• b. Case $\delta \gg \gamma/2$

The typical recording structure is not readily amenable to analytical formulation of its coupling field. This is the case here. Among the various methods available to obtain the coupling field in such cases, the one selected involved the use of a resistor-network analog of the recording structure. A schematic representation of one network configuration is shown in Fig. 3 and a photograph of the actual analog unit itself with the pluggable resistor boards is shown in Fig. 4. A discussion of design considerations for the network configurations is given below.

The original intention was to use the resistor analog to obtain a first approximation to the magnetic-potential distribution (and hence, magnetic field) and refine this data on an electronic calculator. However, the extension of the analog to the degree of precision compatible with the problem and the nature of the experimental data was direct and easily accomplished, and this second phase for the determination of the magnetic field was not carried out, the analog results being quite adequate.

Some advantages of the resistor network are:

- (1) No precise or accurate model of a structure is required and no delicate measuring probes and positioning mechanisms are necessary.
- (2) Relative permeability ratios are easily obtained.
- (3) The model is durable, results easily repeatable, and no physical resemblance need exist.
- (4) The structure established is fairly simply modified. The obvious disadvantage is the initial effort in setting up the plug-board and the resistor-network cards. Certain structures required approximately two-thousand resistors.

The basis of the resistor-network analog is well known. The analogy involves a mesh or discrete structure which is the same type of approximation to a continuum as is made in numerical analysis. Hence, only the basic physical relations which establish the model will be set forth.

In the magnetic case the field of concern is in a region free of current sources. Thus

$$\nabla \times H = 0 \quad (18)$$

and of course

$$\nabla \cdot B = 0. \quad (19)$$

It is assumed $B = \mu H$, where μ is relative permeability and is assumed constant. Then, except at the magnetic boundaries

$$\nabla \cdot H = 0. \quad (20)$$

Equation (20) merely states that in the regions of constant permeability the H field satisfies LaPlace's equation since,

$$\text{setting } H = -\nabla \cdot \phi_m \quad (21)$$

where ϕ_m is the magnetic potential, it is clear that

$$\nabla^2 \phi_m = 0. \quad (22)$$

In a resistor network (passive-element region)

$$\nabla \times \mathcal{E} = 0, \text{ and} \quad (23)$$

$$\nabla \cdot i = 0 \quad (24)$$

where $\mathcal{E}$ is the electric field and i the current density. Since

$$\mathcal{E} = -\nabla \cdot \phi \quad (25)$$

where ϕ is the electric potential, and $i = \sigma \mathcal{E}$ where σ is the conductivity then $i = -\sigma \nabla \phi$, or

$$\nabla \cdot i = -\sigma \nabla^2 \phi = 0. \quad (26)$$

Hence $\phi_m \sim \phi$ and $B \sim i$ in the equivalence. Further, $H = -\nabla \phi_m$ or

$$H_x(x_i, y_i) \propto \phi(x_{i+1}, y_i) - \phi(x_i, y_i)$$

for the horizontal component, using e.g., a forward difference technique with the set of discrete values obtained from the network, etc.

The boundary conditions are of two types. A line of constant magnetic potential is represented circuitwise by a conducting bus (constant voltage), and a line of constant field intensity by a "cut" through the resistor network (a path along which all the connections are broken in the direction normal to the desired field line). This latter procedure constrains the current, which is analogous to flux density, to flow parallel to this boundary as is required. By judicious estimates of the boundary conditions for a structure and through use of shorting or open-circuit paths the actual extent of a structure that must be represented in analog form is generally only a small portion of the total. This fact makes the analog approach feasible to exploit for magnetic-field analysis.

• Resistor analog of ring structures

The basic evaluation of ring structures was carried out by setting up equipotential lines corresponding to the known location of such boundary conditions on the resistor analog.

One basic ring structure studied is the so-called idealized ring. This latter term defines ring-type structures in

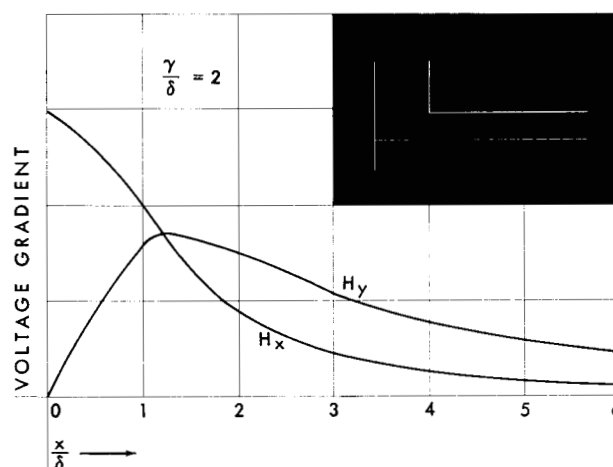
which the recession of the pole faces from the surface is gradual enough that, relative to the other pertinent parameters, the pole faces can be considered to extend infinitely along a plane parallel to the recording surface. Recognizing that these important dimensions range from tenths of a mil up to several mils, it is evident that this approximation is valid for most recording rings.

The special case in which the pole faces recede rapidly is also included for a particular parameter ratio where this type of construction is practical. This latter-type ring head yields a significant improvement in resolution and was the type of head developed for the IBM RAMAC disk file. The theory and description of this unit is covered in Reference 1.

A single idealized ring head may apply to any particular set of parameter values by appropriate scaling of the analog model. Hence, the data taken is in terms of the ratio γ/δ ; the resultant plots then show H_x and H_y for $x/\delta \geq 0$ along a plane spaced δ units from the pole faces. δ is used as a normalization factor. Only positive x need be considered since this ring structure is symmetrical. H_x at any point is defined as the voltage difference across a unit distance (one resistor) in the x direction and H_y as the differential voltage per unit length (one resistor) in the y direction, centered about the plane $y = \delta$. These two field components are plotted as a function of x in Fig. 5 for one particular ratio of γ/δ .

Table 1 gives a summary of the information obtained through measurements of this type. Values preceded by $>$ represent limits set by the physical size of the analog model. The first row $\gamma/\delta \rightarrow 0$ includes the results of the analytical calculations made earlier, while the remaining rows are based upon the model measurements, these cases not being readily amenable to analytical calculation as mentioned previously. Included in this table are columns giving the particular resolutions obtainable where, of course, the resolution factors are now likewise

Figure 5 Analog-model field plots for an idealized ring head.



expressed in a dimensionless form with δ as the basic unit of measure. These factors apply directly only to an infinitesimal storage film.

The correction for recording-layer thickness is essentially a summation of such functions over the depth of the surface, each incremental strip being weighted amplitude-wise automatically through use of relative-magnitude data if the voltage difference applied to the model is held constant for all readings. Thus, as the distance from the gap increases, the relative attenuation of the coupling sensitivity is inherently included. In cases where the surface depth, d , is small relative to γ and δ , the resolution factors may be used directly. In general since δ specifies the center plane of the recording surface, it will give a mean value which represents a reasonable theoretical approximation and in experimental terms will normally be justified as of sufficient precision. Given δ , the actual resolution can be established immediately.

Table 1 illustrates the importance of having only a small vertical-magnetization component after recording due to the broad extent of coupling arising from H_y . The permissible magnitude of M_y is roughly 20% of the total magnetization for all cases, before recording resolution will be impaired with the idealized type of ring head, a figure close to that obtained analytically for the case $\delta \gg \gamma/2$. No definite optimum parameter ratio is indicated for resolution alone, but a ratio of $0 \leq \gamma/\delta \leq 1$ appears to be a reasonable range over which to expect maximum resolution, i.e., a minimum λ_x , assuming the

Table 1 Summary of field-spread measurements for an idealized ring-type head.

γ/δ	λ_x/δ	λ_y/δ^*	H_{xm}/H_{ym}	H_{ym}	$M_y/M_x(\text{max})$ for $\lambda_y = \lambda_x$
0	9.0	40/80	2.0	δ	0.22
0.5	8.5	>10	2.0	δ	0.22
0.67	10.6	>13	2.0	δ	0.2
1	11.0	>20	2.0	δ	0.2
2	13.0	>14	1.75	$3/2\delta$	0.22
4	14.0	>28	1.37	2δ	0.2
8	18.4	>56	1.02	4δ	≈ 0.2

*In the first row δ applies if $M = M_y$.

Table 2 Field-coupling efficiencies for an idealized ring-type head.

γ/δ	$H_g = 100/\gamma$	$H(o)$	$H(o)/H_g$
≈ 0	$*100/k\delta$	$32/\delta = 100/\pi\delta$	≤ 0.1 †
0.5	$200/\delta$	$32/\delta$	0.116
0.67	$150/\delta$	$30/\delta$	0.20
1	$100/\delta$	$28/\delta$	0.28
2	$50/\delta$	$24/\delta$	0.48
4	$25/\delta$	$16.4/\delta$	0.66
8	$12.5/\delta$	$9.7/\delta$	0.78

Gap magnetic potential difference = 100.

* $k = \gamma/\delta$

† $\gamma/\delta \leq 1/3.2$

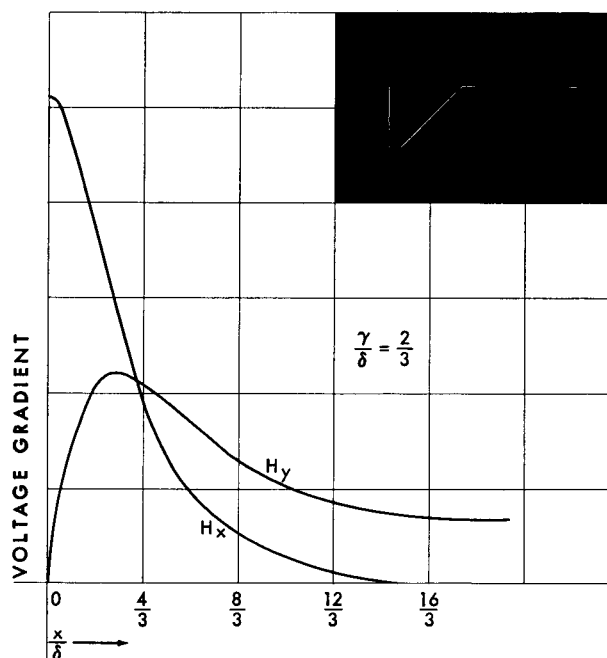


Figure 6 Analog-model field plots for a narrow-pole-tip ring head.

conditions on the ratio M_y/M_x are met. Using the values $\gamma = 1$, and $\delta = 1.5$ then $\lambda_x/\delta \approx 11$ and $\lambda_x = 16.5$. This figure is very representative of the pulse-width response observed (measured at the five-per-cent points) from a step-like change in saturation recording current with these parameter values. Inspection of the column λ_x/δ shows that no significant improvement in resolution can be expected from continued reduction in gap size.

Figure 6 gives the same information for a ring head with tapered pole tips as shown. For the same value of δ and γ , $\lambda_x = 11$. Hence, a 50-per-cent improvement in resolution has resulted from this modification to the pole faces. The restriction on the ratio M_y/M_x is only slightly more stringent. This value for λ_x and the per-cent improvement correlates well with the data obtained in the design of the RAMAC disk magnetic head. In actual practice the distances are in mils with the non-contact values quoted, hence, $\lambda = \lambda_x = 11$ mils.

A salient fact which is evident from these figures is the possible detrimental effect of a vertical magnetization component when using a ring-type head. The value of sharp pole tips when they are practical is also apparent, as well as the relative significance of gap size in relation to spacing when considering resolution.

Table 2 gives a relative measure of coupling efficiency versus the ratio of γ/δ by indicating the coupling sensitivity ratio (maximum field at distance δ to the gap field, i.e., $H(o)/H_g$). These figures are established by assuming a constant potential difference maintained across the gap. The attenuation of the pertinent fringing field as the surface spacing is increased is evident. Due to the fact that the magnetic head has the dual function of writing and

reading, an excellent compromise between resolution and maximum coupling would be a choice for the ratio of γ/δ of 1.0. This data applies equally to contact recording (it should be recalled that δ will always be finite). The dimensions involved in contact recording will, of course, tend to be smaller.

4. Probe structures

Of the three possible directions of surface magnetization, two have the feature that they may be considered design-wise as essentially independent of track width. The magnetic heads corresponding to these two directions of surface magnetization (x direction of surface motion, and y direction) produce output signals directly proportional to the track width. For reasons basically originating with the advantages of bit density over track density only these two methods of storage appear to have any potential merit.

A ring-type head produces primary magnetization along the x axis and this mode of operation is generally referred to as longitudinal recording. This type of record-

ing is universally employed in magnetic data-recording systems today. The previous section on the ring-type head was directed toward the evaluation of this form of recording.

In consideration of the general question of high-density magnetic storage, it is certainly of interest to examine the other possible mode of recording. Since the primary coupling between the head and surface arises from a magnetic field oriented normal to the surface the basic head structure can be likened to a probe. For reasons similar to those dictating the choice of the word "ring" to describe the class of heads which are primarily intended to produce horizontal (or longitudinal) recording because of the basic structure required, the word "probe" will apply to all recording structures designed to produce and sense vertical magnetization.

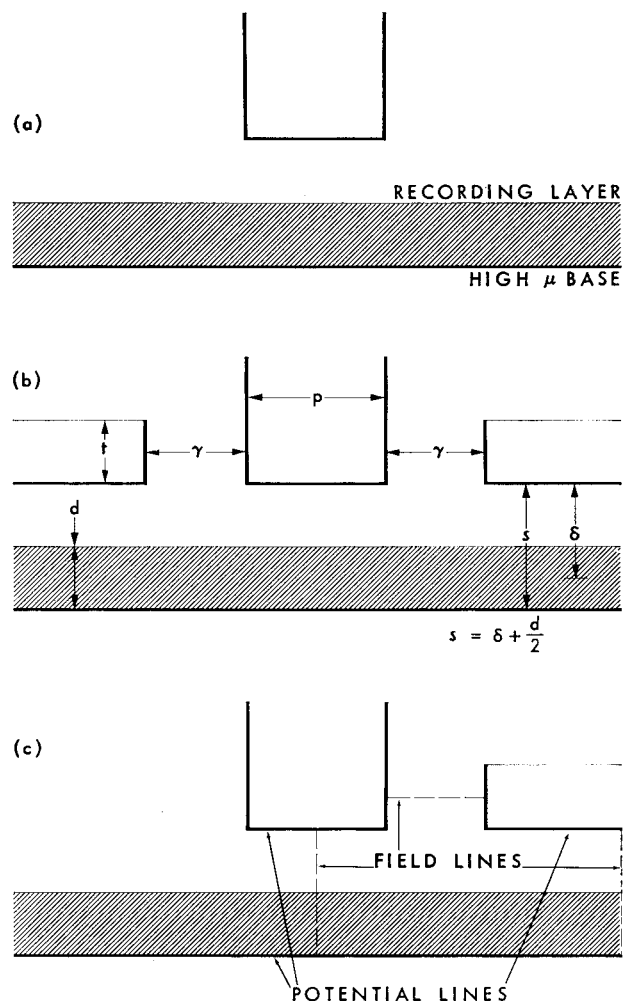
To achieve a strongly localized vertical field through a recording surface with a probe, an "effective magnetic sink" is highly desired. This immediately leads to the selection of a soft magnetic base material to support the storage layer. The structure outlined so far would appear as indicated in Fig. 7(a). For reasonably high permeabilities of the probe and base material relative to air, a constant magnetic potential difference may be assumed to exist between the probe-tip region and an apparent semi-infinite magnetic block.

At this point the question is immediately raised as to what may be done to improve the inherent resolution of this basic structure. Modifications of the probe-surface magnetic configuration shown are, of course, restricted to occur at a distance from the recording layer equal to or greater than the head-to-surface spacing. The coupling-field component of interest with a magnetic probe is H_y . To reduce the spread of H_y , and hence improve resolution, it is noted that if the plane of the probe tip, in the vicinity of the probe but excluding the tip itself, is placed at the same magnetic potential as the base material then no magnetic potential drop exists across the recording surface between the two equipotential planes so established.

This situation is readily visualized in terms of the electrical-resistor analog. The interpretation of this situation yields the conclusion that there is essentially a vertical coupling field only with the surface region directly under the probe tip. The added constant-potential magnetic boundary indicated above could be realized with a soft magnetic (high permeability) slotted sheet which will henceforth be referred to as a magnetic shield or simply a shield. However, it is not only desired to have a constant-potential shield, but also that this magnetic boundary be established at the same magnetic potential as the magnetic base material.

The actual magnetomotive force is set up across the length of the vertical probe. Since the shield is interposed in the return path of the coupling flux, it may be effectively regarded as the magnetic return. From this aspect the magnetic underlayer is floating. Consideration of the electrical analog indicates that the ratio of the effective resistance between probe tip and magnetic base to that

Figure 7 Progressive development of a high-resolution probe.



existing between the base and shield will become increasingly larger as the shield is extended about the probe. Hence, by choosing a shield sufficiently broad compared to the other dimensions the base will assume a magnetic potential value (between that of the probe tip and shield) essentially the same as that of the shield.

While the above line of reasoning has evolved a basic structure one additional parameter must be recognized. A finite separation must exist between the shield and probe. The size of these gaps is subject to somewhat the same considerations as apply to the gap in a ring-type head. Since the probe structure as described is symmetrical, the separation gaps referred to are equal and hence for a probe the word gap in the singular will be used for convenience. The gap size again is based on the competing requirements of resolution and efficiency between the probe coil and the recording surface. This efficiency is of prime interest when writing, since the recording surface must saturate before the probe tip.

Although the result of the train of reasoning above is a basic high-resolution magnetic-probe recording device, it should not be inferred that the actual evolution of such a unit occurs in this manner.

One basic probe structure and pertinent parameters are shown in Fig. 7(b). It is not possible in this case to examine a single configuration and, by mere scaling, have the results apply to any set of parameters as is true with the idealized ring-type head. No simple analytical expression immediately became evident and the theoretical study was carried out on the resistor analog. The area of interest is in only a specific region of the structure.

If we recognize the known boundary conditions which most nearly circumscribe the desired region, the size of the analog network which must be developed need only be a small part of the total area. This fact is illustrated by the outlined zone, with the applicable boundary conditions shown in Fig. 7(c). Advantage is taken of symmetry to consider the one-half plane $x \geq 0$; the measurements made are of voltage differences along a line at a spacing of δ from the magnetic probe, giving the sensitivity functions H_x and H_y . While the primary field component of interest for a probe is H_y , the presence of H_x must also be considered. Typical results obtained are shown in Fig. 8 for selected parameter ratios.

The above data is normalized to the factor s . This parameter is selected since it characterizes the most fundamental external restriction placed on a design.

The cases shown in Fig. 8 are based upon the assumption of an infinite permeability for the soft magnetic materials (probe structure and base material). Deviations from this idealization will be covered later.

One very significant fact is evident from observation of these figures. Both field components yield a similar spread or resolution so that the possible existence of both M_x and M_y in the surface cannot degrade resolution. Rather, the presence of M_x in addition to the principal component M_y will tend primarily to modify the basic read-back wave form (arising from H_y), the marked effect being a tendency to produce base-line distortion in accord

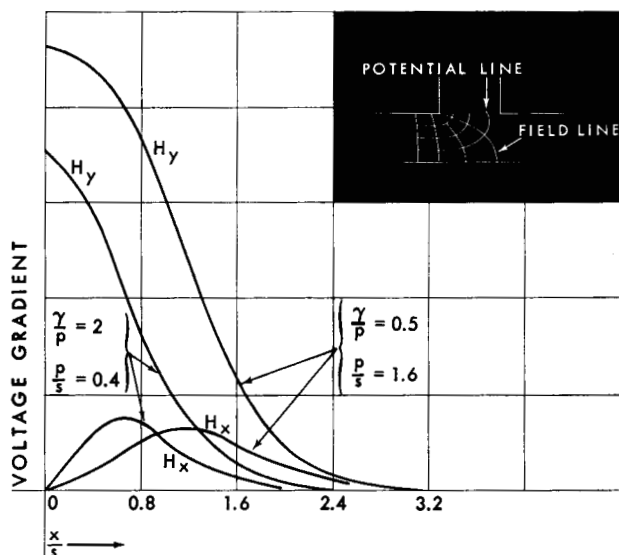


Figure 8 Analog-model field plots for probe.

with the theory outlined earlier. This situation is in direct contrast to that for the ring-type head. To obtain high resolution with a ring-type head it is essential that the surface magnetization be predominantly horizontal. This difference between these two basic structures has significance from the point of view of the recording layer, the implication being that the surface magnetic properties are not as critical in order to obtain the resolution potential inherent in the probe-type structure. The similar attenuation of both the coupling-field components with x represents a predictable advantage for the probe configuration. Another important surface parameter, the depth d , will be discussed separately. The resistor network for one special case is shown in Fig. 3.

Rather than build up the full head structure, the known boundary conditions were employed to reduce the region requiring simulation to the smallest area surrounding the region of interest that could be established. Now the soft magnetic base material is floating with respect to the head insofar as its magnetic potential is concerned. The shield area must be large enough to essentially establish this base material at the same potential as the shield itself. This calls for the effective reluctance between the magnetic base and the shield to be many times less than the effective reluctance between the probe tip and this base. Since the area between the magnetic base and the head shield extends in a circular fashion about the probe, the shield diameter is less than would be indicated from a strictly two-dimensional model. It should be noted that the basic head-design structure involves a narrow slot in the bottom of a circular magnetic cup within which the coil and probe are located (see Fig. 12). The probe tip extends into the slot, forming the basic magnetic-recording configuration.

So as to permit study of the influence of the shield size, an external resistor was connected between the base and shield after the resistor network had been extended

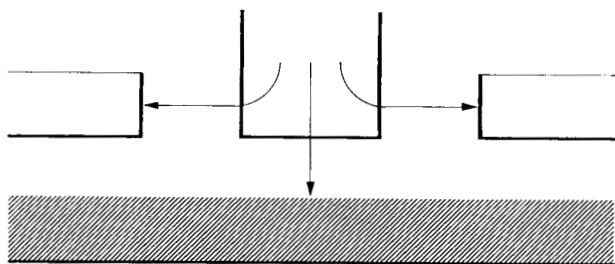


Figure 9 Probe flux division when energized.

along the direction of relative motion (x axis) to the point at which the relative potential gradients were negligible, with a direct electrical short between the base and shield on the analog model. Setting the shield and base at the same potential is equivalent to having an infinite area for the opposing shield-base planes. The next step was to increase gradually the resistance electrically connecting these two zones until a noticeable change in the potential gradients (magnetic field) became evident. The resistance value so obtained was related to an equivalent extent of the shield about the probe in terms of the resistor model. This approach yielded a figure of about $15s$ as adequate for the range of parameters studied. This length must, of course, be maintained throughout the width of the probe. To avoid a shorted-turn effect, the slot must extend appreciably beyond the sides of the probe. In practice, the shield area must be at least as large as the outer diameter of the coil to form the magnetic cup. The shield area must therefore be much larger than is actually required by magnetic considerations. In simulating the probe on the resistor analog, it is adequate to set the base potential at the same value as that of the shield.

The significant parameters in the design of a high-resolution recording probe are shown in Fig. 7(b). The fact that recording resolution involves both the probe and the recording medium is indicated by the enumeration of the pertinent parameters associated with each. The shield thickness, t , enters the design of the probe through its influence on writing. The total writing flux established in the probe proper on writing divides among the paths indicated in Fig. 9. To obtain efficiency in achieving the requisite writing field, it is necessary that t be small. The basis for the choice of t is governed by writing, and this variable does not appear in the general considerations of resolution.

The sensitivity functions H_x and H_y are obtained by measuring the appropriate voltage differences along the surface plane corresponding to a spacing of δ for various parameter ratios. The actual values of the dimensions involved range from fractions of a mil to several mils and therefore, in accordance with current fabrication techniques, only the simple structural geometry indicated in Fig. 7(b) was considered.

The number of significant parameters and their interdependence is such that even with this structure, scaling of one configuration is not sufficient as was the case with

the idealized ring-type head. Typical plots of H_x and H_y for certain parameter ratios are shown in Fig. 8. The change in the wave form of $e(\sim H_y)$ for pure vertical magnetization with the ratio of γ/p should be noted. For γ less than p the signal tends to have a bell-shaped peak, while for γ greater than p the pulse tends to have a triangular peak. The shape of this wave form is important in establishing the amplitude drop-off characteristic versus the density of alternating step-like changes in magnetization on read back. From superposition it would be expected that the rounded top would produce a more rapid attenuation of amplitude with this density once pulse interference commences, and this proves to be the case. The insert is a qualitative field plot for the model of the probe assumed here which graphically illustrates the coupling magnetic field.

On the basis of measurements made of many representative structures simulated on the analog model, the following relation appears to give most simply an adequate approximation of head resolution in terms of the dimensional parameters

$$\lambda \approx 2[p/2 + \gamma + \delta] \quad (27)$$

where the factors giving λ are defined in Fig. 7(b). λ is thus given by the sum of the slot width plus 2δ . Now $\delta = s - d/2$, and $0.5 < \delta/s < 1.0$. The thickness d does not need to appear explicitly in the expression for λ . Only λ is necessary since $\lambda_x = \lambda_y = \lambda$. This equation, of course, does not apply for an unshielded probe, i.e., $\gamma \rightarrow \infty$. For this case a new relation applies in which a new variable, specifying the location of the coil along the length of the probe, must be introduced. Where the shield is feasible, experimental results indicate a gain in resolution by a factor of from two to four.

Information on the actual thickness needed for the soft magnetic base is of practical importance. This question can be studied readily on the resistor-network model. Let D represent the thickness of this base material, where the physical support for this base, being non-magnetic, will have a relative permeability of one. To study the influence of D , it is clear that a finite value must be assigned to the permeability of the magnetic base layer. When $D=0$ the probe head will appear to behave similar to two adjacent ring-like heads with one physically common magnetic branch. The advantages of the probe are lost in this case. Figure 10 gives the relative amplitude of $H_{y\max}$ as a function of D for an assumed relative permeability of 50 for the soft magnetic base. The applied potential difference was held constant. For this particular structure under this condition, it is seen that D need only be equal to or greater than p in order to assure the full effectiveness of the magnetic base. For D less than this the effective vertical-field coupling with the storage layer drops rapidly. This effect is accompanied most noticeably by a great increase in λ_x , associated with an increase in the ratio $H_{x\max}/H_{y\max}$. The effect of permeability is simulated on the resistor analog by selection of resistor ratios. The relative permeability of two different media is given by the inverse ratio of the resistor values.

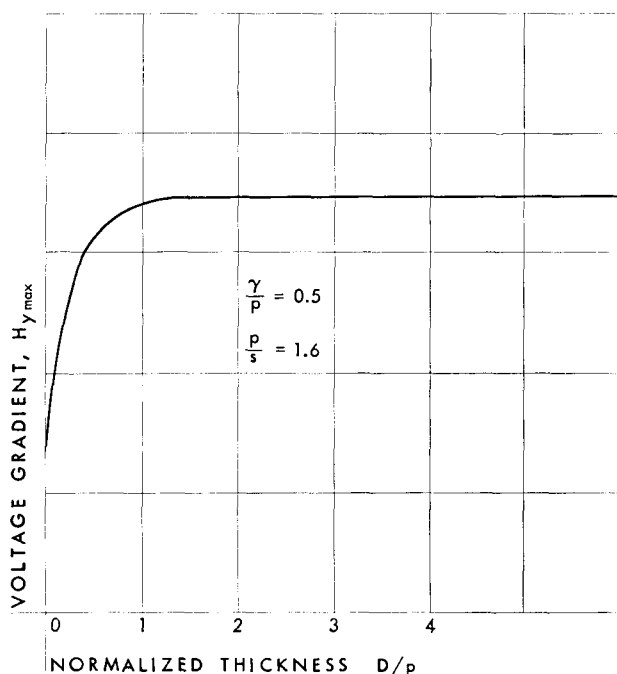


Figure 10 Probe-coupling efficiency versus base thickness, analog model.

Figure 11 indicates the differences in the H_y field measurements along the plane δ when an infinite-permeability probe and shield are replaced by one having a relative permeability of 10. In this case the mmf was applied at the probe cross section corresponding to the coil's lower boundary in an actual structure. This permeability ratio is low enough that an appreciable loss in resolution would be expected. Increasing the ratio to 50 restores the resolution to a value close to that for the infinite-permeability case.

With a probe, the recording layer is magnetized normal to its plane and the question of demagnetization must be treated individually from the considerations applicable to a ring head since the orientation of the magnetization in the latter case is primarily in the plane of the surface. Since d must be small for effective head-surface coupling, the demagnetizing field will be much larger relative to that existing with longitudinal recording at equivalent densities. The actual influence of demagnetization on recording performance is not clearly evident. Recording on different recording thicknesses indicated that an optimum value for d exists. The signal attenuation as d is increased beyond some point can be understood in terms of the loss in coupling efficiency. As d is reduced it is likewise expected that loss in signal will result due to a reduction in the volume of magnetization providing the residual surface field after writing. This effect may likewise be viewed in terms of the opposing fields set up by the opposite magnetic-pole distributions on the upper and lower recording-layer boundaries. Since this effect goes contrary to the variation in coupling efficiency some optimum range of recording-layer thickness may be pre-

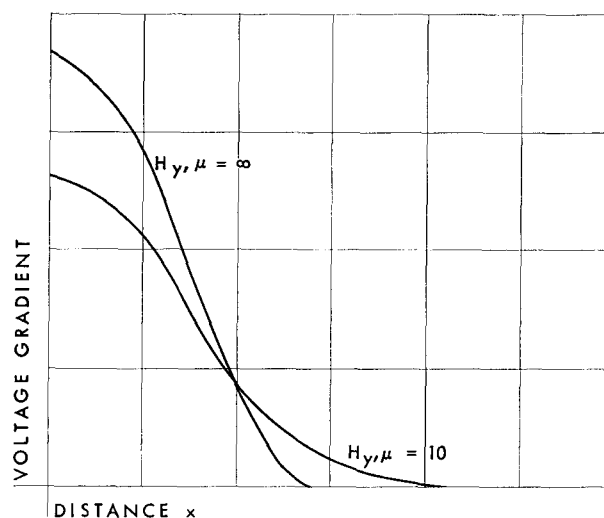
dicted for structures otherwise completely specified. However, demagnetization exists and is certainly related to the volume and distribution of vertical magnetization. Calculations have been made on the factors influencing the selection of d but no comprehensive tests have been made which allow a firm determination of the actual influence of self-demagnetizing fields. Experiments do definitely give a best choice for d based on a maximum amplitude. For a value of d of less than this figure the output signal decreases markedly. The degree of correlation between the analytical expression (equation 27) and experimental results from probes with varying sets of parameter ratios was within 10%. A rough balance among the influences of the individual terms generally establishes the configurations of interest. The value of the shield in increasing resolution is associated with the restraints that may exist upon certain parameters.

Parameter t is established by a continual reduction in shield thickness interposed with recording tests. t is fixed at the value for which no further increase in signal is obtained. At this point the percentage of the saturation probe flux contributing to the writing field is sufficient to insure that the recording surface will definitely saturate before the probe tip. A schematic view of the probe head structure is given in Fig. 12, and a photograph of an actual unit appears on page 90.

5. Wire-grid structures

The conceptual approach involved here essentially is one of attempting to beam or focus a magnetic field. That is, rather than continually attempt to reduce size to obtain higher resolution, the transducer is composed of an array of sensitive elements. The objective is to obtain a cancellation effect everywhere except at a focal point by proper superposition of the responses of the field-sensitive receptors. This technique would then possess the capability of overcoming non-contact operations to some extent.

Figure 11 Resolution variation with probe permeability, analog model.



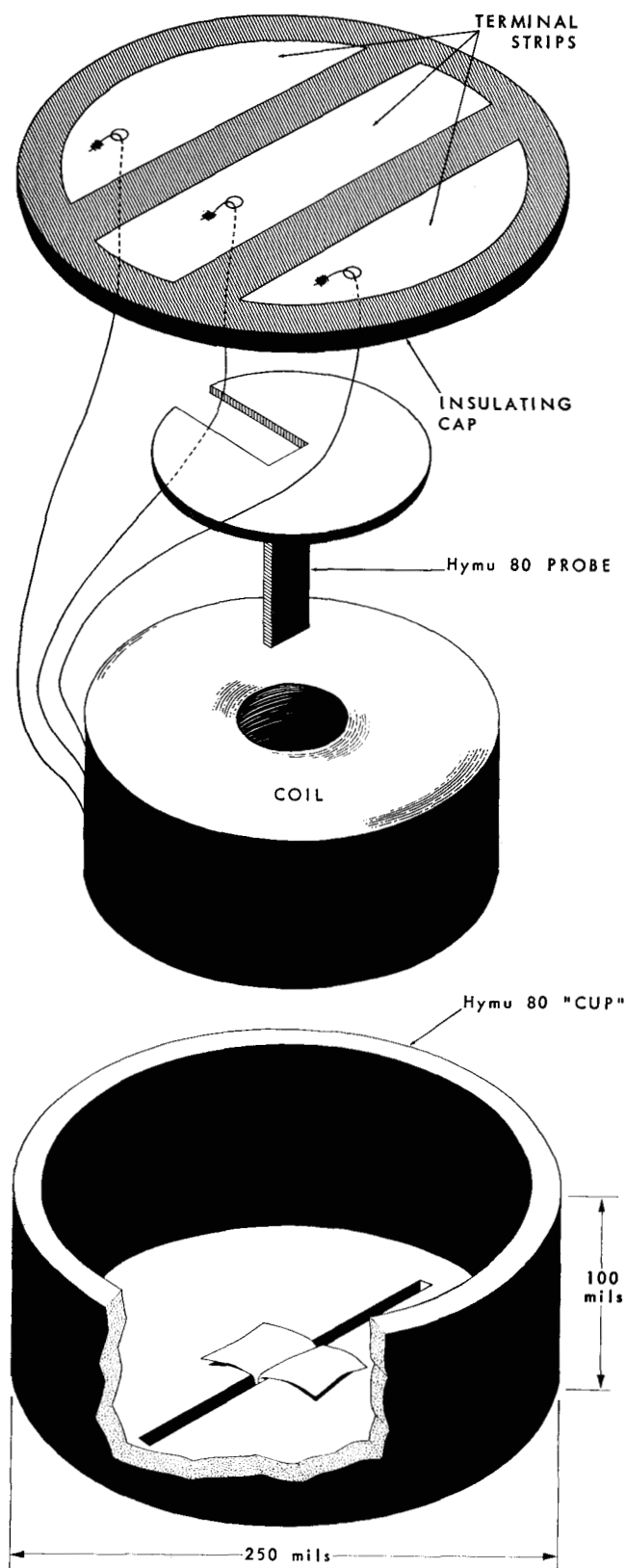


Figure 12 Design of probe-type recording head.

This device can be evaluated approximately as two-dimensional due to the usual bias in favor of bit density per track over track density, mentioned previously. The problem will first be formulated in a general manner using the reciprocity concept which here will apply rigorously, as the transducer will be considered as a current sheet, parallel to the storage surface, wherein the current will be a function of x , i.e. $I(x)$. By the reciprocity concept this current distribution would correspond to the desired relative weighting function for the signals induced in the corresponding filamentary current strips before their combination on read back.

Formulation of the general problem leads to a physically unrealizable optimum. A complete mathematical design of a wire-grid head will be given which yields increased resolution over a single-wire head. Consider Fig. 13(a).

Now

$$d\bar{H} = \frac{I(x)dx}{2\pi(\delta^2 + x^2)^{\frac{1}{2}}} \quad (28)$$

where

$$\int_{-\infty}^{\infty} H_y dx = 0 \text{ along any } y \text{ plane.} \quad (29)$$

Now for a single-frequency spatial component of periodicity β_i it may be shown that the following relation exists between the amplitude coefficients of H_x and I_i (H_{x_i} and I_i are of the same frequency and phase)

$$I_{m_i} \propto H_{x_{m_i}} e^{2\pi\delta/\beta_i}. \quad (30)$$

Consider the achievement of the following desirable coupling function

$$H_x = \begin{cases} K|x| \leq \varepsilon \\ 0|x| > \varepsilon \end{cases} \text{ where } \varepsilon \text{ is a free parameter.}$$

Let

$$2\pi/\beta_i = v_i.$$

Then

$$H_m(v) \propto \frac{\sin v}{v}$$

and by equation (30)

$$I_m(v) \propto \frac{\sin v}{v} e^{v\delta}. \quad (31)$$

However

$$I_m(v) \rightarrow \infty \text{ as } v \rightarrow \infty$$

so that an exact solution does not exist, there being a divergence of the series coefficients. Further, the conversion of a wave-length distribution of I into the corresponding distribution in x is not obvious. The general effect of increasing the spacing δ is to accentuate the short-wave-length components of $I(v)$. However, this general concept of obtaining increased resolution may be usefully demonstrated in simple discrete structures.

Consider a single wire (Fig. 13b)

$$H_x = \frac{I}{2\pi\delta} \cdot \frac{1}{1+(x/\delta)^2} = K \frac{1}{1+(x/\delta)^2} \quad (32)$$

Let $x/\delta = u$.

Then the resolution is equal to $9u$, using the five-per-cent points. This assumes that $M=M_x$ and the wire diameter is much less than δ .

To improve the resolution let us form a grid where we introduce two additional sources to give $H_x \approx 0$ at $u=1$, i.e.

$$\begin{array}{c} -1 \quad +2 \quad -1 \\ \otimes \leftarrow \delta \rightarrow \odot \leftarrow \delta \rightarrow \otimes \end{array}$$

where the numbers indicate the relative strengths of the sources. By superposition (see Fig. 13c) the recording resolution will be approximately $6u$.

This grid structure thus has a resolving power 50 per cent better than that of a single wire. Note that the sources are such that at large distances the total structure appears to be a zero net source.

Under a less stringent criterion for the determination of recording resolution, the relative improvement of the wire grid over a single wire appears more striking. With resolution defined as the distance between the 10-per-cent points, the gain in resolution is a factor of three.

It must be remembered that the above approach to design is one based on reciprocity. Here, however, writing fields would be similar to the response diagram for H_x since the current array will behave linearly. The same structure would therefore yield a higher-definition writing field. An oriented surface would enhance the possibility of neglecting H_y since again maximum resolution is obtained when $M=M_x$. It is clear this design approach has broad implications, the above structure representing only a theoretical example. One modification immediately apparent would be the employment of a high permeability block for the support of the wire grid. On the basis of image theory this would increase the coupling between the grid and surface by a factor of two. This approach also applies to sources disposed at different distances from the storage surface and likewise to elementary receptors which may include magnetic paths. For the wire-grid design discussed here the source density at the center is achieved by a number of parallel elements at the source location. Series-aiding connections of these wires are used. The negative coefficients of the sources at $\pm\delta$ are achieved by utilizing series-opposing interconnections in these grid sections. The complete design would appear as shown in Fig. 13(d).

6. Conclusions

This paper has attempted to describe in some detail the design theory of magnetic-recording structures directed towards maximizing bit density. The design of the conventional ring-type head has been fairly comprehensively treated. Two more unusual approaches have been advanced and likewise evaluated. These are the probe and

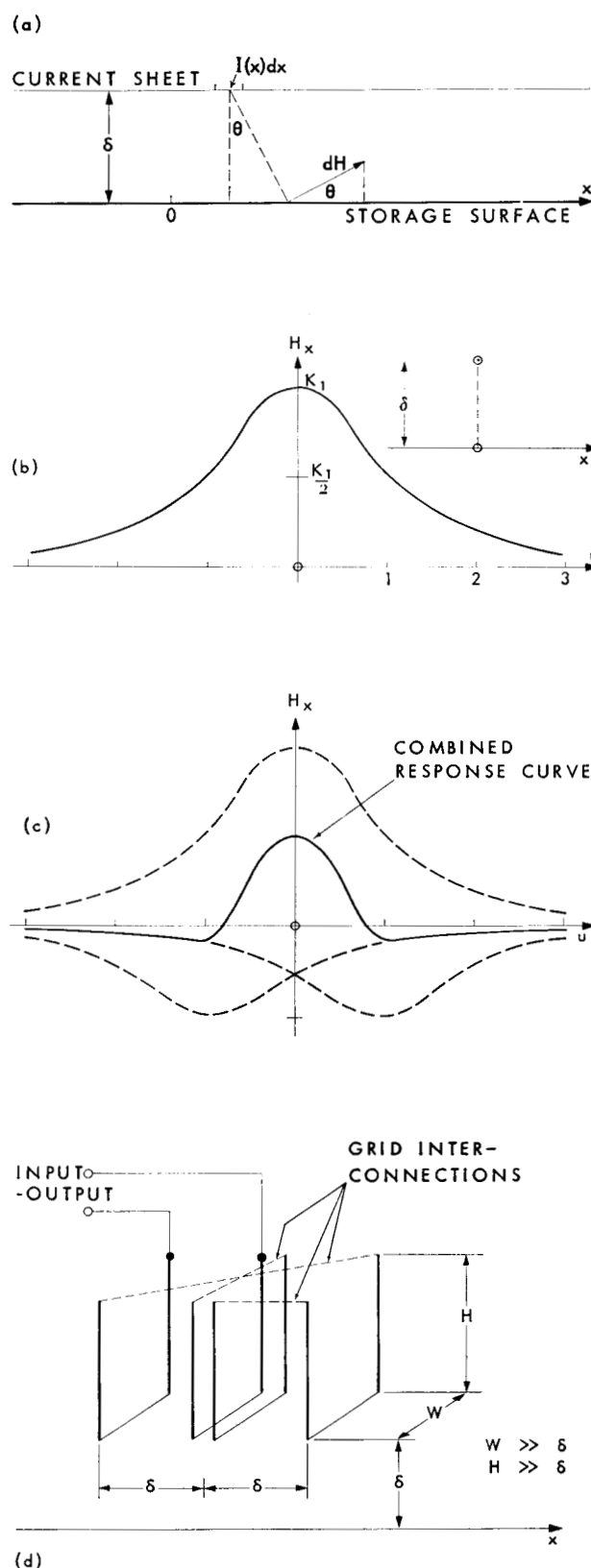


Figure 13 Progressive evolution of the wire-grid structure.

the wire-grid structure. The wire-grid approach was primarily intended to advance a somewhat different conceptual approach to the problem of obtaining higher resolution.

The probe device has been specifically designed and developed to provide high resolution. This unit represents a significant advance in the state of the art of magnetic recording over the ring-type head in several respects. One significant aspect of this probe is its more favorable situation with regard to the magnetic properties of the recording surface. The basic unit has the merit of being a relatively simple structure. The analyses given provide a rapid means of evaluating ring and probe structures with respect to recording resolution, knowing the existing state of fabrication technology.

The fundamental theory and design methods used here are the same as those developed in Reference 1 and this paper extends and reinforces their basic merit.

Acknowledgment

I would like to sincerely acknowledge the efforts of D. Sliter who performed much of the experimental work.

The capsule method of fabrication for the probe evolved from close collaboration between D. Sliter, R. Rogers, and the author.

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